INFLUENCE OF SHRINKAGE AND SWELLING PROPERTIES OF COAL ON GEOLOGIC SEQUESTRATION OF CARBON DIOXIDE

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ABSTRACT

The potential for enhanced methane production and geologic sequestration of carbon dioxide in coalbeds needs to be evaluated before large-scale sequestration projects are undertaken. Geologic sequestration of carbon dioxide in deep unmineable coal seams with the potential for enhanced coalbed methane production has become a viable option to reduce greenhouse gas emissions. The coal matrix is believed to shrink during methane production and swell during the injection of carbon dioxide, causing changes in the cleat porosity and permeability of the coal seam. However, the influence of swelling and shrinkage, and the geomechanical response during the process of carbon dioxide injection and methane recovery, are not well understood.

A three-dimensional swelling and shrinkage model based on constitutive equations that account for the coupled fluid pressure-deformation behavior of a porous medium was developed and implemented in an existing reservoir model. Several reservoir simulations were performed at a field site located in the San Juan basin to investigate the influence of swelling and shrinkage, as well as other geomechanical parameters, using a modified compositional coalbed methane reservoir simulator (modified PSU-COALCOMP). The paper presents numerical results for interpretation of reservoir performance during injection of carbon dioxide at this site. Available measured data at the field site were compared with computed values. Results show that coal swelling and shrinkage during the process of enhanced coalbed methane recovery can have a significant influence on the reservoir performance. Results also show an increase in the gas production rate with an increase in the elastic modulus of the reservoir material and increase in cleat porosity. Further laboratory and field tests of the model are needed to furnish better estimates of petrophysical parameters, test the applicability of the model, and determine the need for further refinements to the mathematical model.

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INTRODUCTION

It is believed that the geologic sequestration of carbon dioxide in unmineable coal seams is a new option to reduce green-house gas emissions. Coal seams can hold large amounts of carbon dioxide in comparison to the amounts of methane gas that they contain (Burruss, 2003). However, before commercial sequestration projects are undertaken, it is necessary to evaluate the consequences of the geologic sequestration of carbon dioxide. Several efforts have been made in the past to investigate different technical issues related to carbon dioxide sequestration in unmineable coal seams (Bromhal et al., 2003; Mavor et al., 2004; Gorucu et al., 2005; Reeves and Oudinot, 2005; Siriwardane et al., 2006).

Coal swelling and shrinkage is considered as one of the potential problems during the carbon dioxide sequestration (Reeves and Oudinet, 2005; Smith et al., 2005; Kelemen et al., 2006; Mazumder, et al., 2006a; Mazumder et al., 2006b; Pan and Connell, 2006). Several laboratory experiments and numerical studies indicate that coal undergoes simultaneous swelling and shrinkage when the carbon dioxide is injected into a coal seam while the methane is produced. However, these aspects of carbon dioxide sequestration are still ambiguous. This paper presents a study on the combined influence of various parameters, including elastic modulus, cleat porosity, and permeability, on coal swelling and shrinkage.

A three-dimensional swelling and shrinkage model was developed to study the influence of various parameters. The model is based on the constitutive equations which account for the coupled fluid pressure-deformation behavior of a porous medium that undergoes swelling and shrinkage. For the purpose of this work, the field project of the Allison ECBM unit located in the San Juan basin was selected (Reeves and Oudinot, 2005; Reeves et al., 2003). Several analyses were carried out using the new swelling and shrinkage model that was implemented in an exiting reservoir simulator (Manik et al., 2002). Numerical results obtained from these simulations are compared with previous studies published in the literature (Reeves and Oudinot, 2005; Reeves et al., 2003).

METHODOLOGY

A generalized three dimensional swelling and shrinkage (SS) model was developed and has been implemented in an existing coalbed methane reservoir simulator, PSU-COALCOMP, which has been used in several previous studies (Bromhal et al., 2003; Gorucu et al., 2005; Siriwardane et al., 2006). The SS model is based on constitutive equations that account for the coupled fluid pressure deformation behavior of a porous medium that undergoes swelling and shrinkage. Other treatments of swelling and shrinkage (Painter and Shenoy, 1995; Palmer and Mansoori, 1996; Palmer, 2006) indicate that the coal swelling may cause a reduction of permeability, which in turn may reduce injection volumes during large-scale sequestration operations.

The swelling and shrinkage strains are computed on the basis of the amount of CO_2 sorbed and the amount of CH_4 desorbed. In the SS model, the swelling and shrinkage strains of the coal matrix are expressed as given below.

The swelling strain:

$$d\varepsilon_v^{sw} = C^{sw}\, dV_a \qquad \text{.................................} \; (1)$$

where

ε_v^{sw} = volumetric swelling strain

C^{sw} = swelling constant

V_a = adsorbed volume of the gas that causes swelling of the coal matrix

The shrinkage strain:

$$d\varepsilon_v^{sh} = C^{sh}\, dV_d \qquad \text{.................................} \; (2)$$

where

ε_v^{sh} = volumetric shrinkage strain

C^{sh} = shrinkage constant

V_d = desorbed volume of the gas that causes shrinkage of the coal matrix

Coal swelling is observed when one or both of the gases (carbon dioxide or methane) are sorbed into the coal matrix. Similarly, coal shrinkage is observed when one or both of the gases (carbon dioxide or methane) are desorbed. Equations (1) and (2) allow for the possibility of "swelling or shrinkage" to occur along different paths during the process of sorption and desorption; the sorption may not be reversible, and/or the constants for shrinkage and swelling may have different absolute values. More details on the mathematical formulations can be found elsewhere (Siriwardane et al., 2006).

The change in effective stresses and pore pressure results in coal matrix strains. The constitutive equations for the coal matrix in the incremental form can be written as:

$$d\sigma_{ij} = 2G\, d\varepsilon_{ij} + \left(K - \frac{2G}{3}\right) d\varepsilon_{kk}\, \delta_{ij} + \alpha\, dp\, \delta_{ij} - C^{sw} f_1'(p) dp\, K\, \delta_{ij} + C^{sh} f_2'(p) dp\, K\, \delta_{ij}$$

$$\text{..................................} \; (3)$$

where

σ_{ij} = stress tensor

ε_{ij} = strain tensor

p = pore pressure

G = shear modulus

K = bulk modulus
α = poroelastic constant

The permeability of the material was assumed to vary according to the cubic equation (Palmer and Mansoori, 1996) as shown below:

$$k = k_0 \left(\frac{\phi}{\phi_0} \right)^3 \qquad \text{……………..…..… (4)}$$

In this study k_0 is the reference state permeability and ϕ_0 is the reference state cleat porosity. This model was implemented into an existing reservoir simulator.

SITE CHARACTERISTICS

Previous studies on the performance of numerical schemes used in the SS model show satisfactory performance over a wide range of parameters. In order to further investigate the influence of coal swelling and shrinkage on the reservoir performance, the Allison unit project site located in the San Juan basin (Reeves et al., 2003) was selected. This project involves injection of carbon dioxide into a coal seam as a part of an enhanced coalbed methane production project. Several analyses of the above field site have been reported in the literature (Reeves et al., 2003; Reeves and Oudinot, 2005).

The present study is based on the geometric details of the reservoir which have been reported in the literature (Reeves et al., 2003). Figure 1 shows the grid-block configuration of the reservoir used in the analysis. The number of grid blocks specified in ‘x’ and ‘y’ directions are 33 and 32, respectively. The dimensions of the grid blocks were chosen to have a refined grid in the middle of the reservoir. The irregular geometry of the reservoir was modeled by using active and inactive grid blocks as shown in Figure 1. In this figure, ‘0’ indicates an inactive grid block, and ‘1’ indicates an active grid block without a well. The negative integer ‘-n’ indicates an active grid block with the well # n. These well identification numbers used in the present study are different from the reference numbers used in previous studies. The well numbers listed in the oval callouts (in circles) represent the well numbers used in the earlier reservoir field studies. POW represents the “pressure observation well”.

Reservoir characteristics and other pertinent information such as cleat porosity and permeability at this site can be found elsewhere (Reeves et al., 2003; Reeves and Oudinot, 2005). As illustrated in the Figure 1, the Allison-Enhanced Coal- bed Methane unit consists of 16 production wells, 4 injection wells (#140-#143), and one pressure observation well (POW). Table 1 illustrates the reservoir and fluid properties used as an input in the present study. In the present numerical study, the cleat porosity was varied in the range of 0.2% to 0.4%. One of the important geomechanical parameters influencing the reservoir performance is the elastic modulus of coal. Published literature on the elastic parameters of the coal can be found elsewhere (Levine, 1996). Limited information is available in the literature on the actual values of swelling and shrinkage of the coal. Therefore, different values of swelling and shrinkage constants were assumed in the analysis in order to match the published literature for this site.

The details of reservoir modeling can be found elsewhere (Manik et al., 2002). The flow behavior of the reservoir can be modeled by using two different approaches: (a) specification of known gas production and injection rates, or (b) specification of bottom hole pressure at production and injection wells. Both of these approaches were used in the history-matching of reservoir data. Specific details relevant to the case study are given below.

CASE STUDIES

The influence of the coal swelling and shrinkage on the reservoir performance of the reported field project was investigated in two different phases – Phase 1 and Phase 2. In Phase 1 of the study, the analyses were performed by prescribing gas flow rates (gas production rates and gas injection rates) for each well. For different values of reservoir porosities, the reservoir pressure was computed by assuming different values for the swelling and shrinkage coefficients. The computed values of the bottomhole pressures were compared with the reported data. In order to determine the influence of the cleat porosity on the bottomhole pressure, three different cases were considered with different values of swelling and shrinkage as shown in Table 2. A Young's modulus value of 4,000,000 psi was assumed throughout this phase of the study.

In the second phase of the study, the analyses were performed by prescribing the bottomhole pressures for each well. From the previous studies (Reeves et al., 2003; Reeves and Oudinot, 2005), a few pressure data are available for this study. This limits the scope of investigation of the influence of coal swelling and shrinkage on the reservoir performance. However, in the work reported herein, reservoir pressures prescribed for each well were obtained by combining the measured results and simulated results obtained from the previous studies (Reeves et al., 2003; Reeves and Oudinot, 2005).

Figure 2 shows the assumed reservoir pressure that was used as an input at producer well # 113 for phase 2 of the study. Bottomhole pressures obtained from previous simulations (Reeves et al., 2003; Reeves and Oudinot, 2005) were adjusted before 3,420 days. After 3,420 days, the measured values of reservoir pressure (as reported in the above literature) were used. A few adjustments were made before 3,420 days to obtain the same gas production rate as reported in the previous study (Reeves et al., 2003; Reeves and Oudinot, 2005). However, after 3,420 days, the measured values of bottomhole pressure were used as input. In order to investigate the influence of elastic parameters on the reservoir performance, the elastic modulus was varied, with lower and upper values of 493,000 psi and 725,000 psi, respectively. The above values were obtained from the published literature (Levine, 1996). A Young's modulus value of 521,000 psi was reported for a coal sample investigated in this field site (Levine, 1996).

RESULTS AND DISCUSSIONS

Figure 3 shows the influence of porosity on the bottomhole pressure obtained in phase 1 of the study. The bottomhole pressure shown in Figure 3 corresponding to the porosity of 0.2% compares well with computed values reported in the literature (Reeves et al., 2003) for the first 1500 days and with the reported field measurements after 3500 days.

During the first phase of the study, the influence of cleat porosity on reservoir pressure was investigated. The influence of cleat porosity on the reservoir pressure is shown in Figure 3. As can be seen from this figure, the reservoir pressure is sensitive to the cleat porosity of the reservoir. Bottomhole pressures decreased with the increase in the cleat porosity for the reservoir properties assumed in the study. Also, coal swelling and shrinkage had a significant influence on the computed reservoir pressures. An increase in the swelling coefficient decreased the reservoir pressure, while an increase in the shrinkage coefficient increased the bottomhole pressure. The above results were based on the assumed elastic properties and assumed values of swelling and shrinkage constants. The cleat porosity of 0.2% appears to give the best fit with measured gas production rate. This porosity value falls well within the range reported elsewhere (Reeves et al., 2003).

During Phase 2 of the study, gas flow rates were computed and compared with the actual field production rates. The cleat porosity was assumed to be constant throughout the reservoir. Figure 4 shows the influence of cleat porosity on gas production rate at well # 113. Figure 5 shows the influence cleat porosity on the cumulative gas production rate for all wells. Results show that reservoir cleat porosity has a significant influence on the gas production with time. An increase in the gas production rate with the decrease in the cleat porosity can be seen from these figures.

Analyses were also carried out to determine the influence of elastic parameters on the performance of the reservoir. A lower and upper bound values of 493,000 psi and 725,000 psi were used, respectively. A Young's modulus value of 521,000 psi was reported for a coal sample from this field site (Levine, 1996). Variation of gas production rate at the producer well # 113 is shown in Figure 6 for the above values of Young's moduli. Figure 7 shows the influence of Young's modulus on the total gas production rate of all producer wells. Numerical results obtained from these figures show an increase in the gas production rate with increase in the elastic modulus of the coal. Also, it can be seen in both Figures 6 and 7 that the gas production rate corresponding to Young's modulus of 521,000 psi is close to the measured field production data (Reeves et al., 2003; Reeves and Oudinot, 2005) for the assumed values of swelling and shrinkage constants. It is interesting to note that the elastic modulus of coal reported elsewhere (Levine, 1996) based on measurements gives an excellent fit to the field data on gas production.

Figure 8 shows the influence of shrinkage constants on the gas production rate at producer well # 113. Young's modulus of 521,000 psi was used for the reservoir. Figure 9 shows the influence of the shrinkage on the total gas production rate. The sensitivity of production rate to the shrinkage values can be seen from both the figures. An increase in the production rate is seen with the increase in shrinkage values. These results show that the shrinkage constant has a significant influence on the computed gas production rate. The shrinkage constant (C^{sh}) of 3.0 x 10^{-5} ton/scf gives an excellent fit to the measured gas production rate at the field site.

SUMMARY AND CONCLUSIONS

A generalized three dimensional swelling and shrinkage (SS) model was developed and has been implemented in an existing coalbed methane reservoir simulator, PSU-COALCOMP. This reservoir model was used in the present study. The influence of the coal swelling and shrinkage on the reservoir performance of a reported field project was investigated. Results show that the reservoir cleat porosity has a significant influence on the computed reservoir pressure. Bottomhole pressures decreased with the increase in the cleat porosity. Also, the bottomhole pressure was sensitive to swelling and shrinkage coefficients. An increase in the swelling coefficient decreased the reservoir pressure, while an increase in the shrinkage coefficient increased the bottomhole pressure.

Influence of reservoir cleat porosity on production rate of individual wells as well as the cumulative gas production rate was investigated. Numerical results show that reservoir cleat porosity has significant influence on the gas production rate. The gas production rate appears to increase with a decrease in the initial cleat porosity (ϕ_0). This may be due the fact that the ratio (ϕ/ϕ_0) becomes larger for lower values of (ϕ_0). This in turn increases the permeability of the reservoir, as shown in Equation 4. Also, analyses were carried out to determine the influence of elastic parameters on the performance of the reservoir. Results in the paper show an increase in the gas production rate with the increase in the elastic modulus of the coal for the range of values used in the study.

This paper shows that the cleat porosity, elastic modulus, swelling and shrinkage coefficients – all had a significant influence on the reservoir performance. The bottomhole pressures and flow rate are very sensitive to the above parameters. Hence, the actual properties of the reservoir need to be determined accurately. Also, long-term monitoring of the coal seam would help thoroughly understand the influence of swelling and shrinkage of coal on carbon dioxide sequestration.

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Table 1: Assumed Reservoir and Fluid Properties

Reservoir Thickness	44 ft
Coal-cleat porosity	0.2% - 0.4%
Depth	3440 ft
Initial Reservoir Pressure	1650 psia
Rock Density	1.4 g/cm^3
CH_4 Sorption Volume constant	400 SCF/ton
CH_4 Sorption Pressure constant	514 psia
CO_2 Sorption Volume constant	584 SCF/ton
CO_2 Sorption Pressure constant	250 psia
Sorption time constant	10 days
Reservoir temperature	120 ^{o}F
Wellbore Radius	0.46 ft – 0.58 ft
Skin	1 -10

Table 2: Assumed Elastic, Swelling and Shrinkage Properties

	Young's modulus (psi)	Poisson's ratio	CH_4 Swelling Constant,C^{sw} (ton/scf)	CH_4 Shrinkage Constant,C^{sh} (ton/scf)	CO_2 Swelling Constant,C^{sw} (ton/scf)	CO_2 Shrinkage Constant,C^{sh} (ton/scf)
SS1	0.4E7	0.3	8.0E-05	8.0E-05	4.0E-04	4.0E-04
SS2	0.4E7	0.3	3.0E-05	3.0E-05	1.0E-04	1.0E-04
SS3	0.4E7	0.3	0	0	0	0

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	
1	0	0	0	0	0	1	1	1	1	-9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	[illegible]	0	0	0	1
2	0	0	0	0	1	1	1	1	1	1	[illegible]	1	1	1	1	1	1	1	112	1	1	1	1	-11	1	1	1	1	1	101	1	0	0	2
3	0	0	0	0	1	1	-8	1	1	1	104	1	1	1	1	1	1	-10	1	1	1	1	111	1	1	1	1	1	-12	1	1	0	0	3
4	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	4
5	0	0	1	1	106	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	5
6	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	6
7	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	[illegible]	1	1	1	1	0	0	0	0	7
8	0	1	1	1	1	1	1	1	130	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	114	1	1	1	1	1	0	0	0	8
9	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	142	[illegible]	1	1	1	1	1	-2	1	1	1	1	1	1	0	0	0	9
10	0	1	1	1	1	1	1	1	1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	10
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-17	1	1	1	1	1	1	1	1	1	1	1	115	1	1	0	0	11
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	12
13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-13	1	1	0	13
14	1	1	1	1	1	131	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
15	1	108	1	1	1	1	1	1	1	1	141	[illegible]	1	1	1	1	1	1	1	1	1	1	1	POW	1	1	1	1	1	1	1	1	1	15
16	1	[illegible]	1	1	1	1	-7	1	1	1	1	1	1	1	1	1	113	1	1	1	1	1	1	1	1	[illegible]	1	1	1	1	1	1	1	16
17	1	1	-6	1	1	1	1	1	1	1	1	-20	1	1	1	1	1	1	1	1	1	1	1	1	1	140	1	1	1	1	1	1	1	17
18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-5	1	1	1	1	1	1	1	1	[illegible]	1	1	1	1	1	1	1	1	18
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21	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
22	0	0	0	0	1	1	1	1	1	1	132	1	1	1	1	1	1	1	1	143	1	1	1	1	1	1	1	1	1	1	102	1	1	22
23	0	0	0	0	1	1	1	1	1	1	[illegible]	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23
24	0	0	0	0	0	0	1	1	1	1	1	-4	1	1	1	1	1	1	-19	1	1	1	1	-3	1	1	1	1	1	1	1	-14	1	24
25	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	[illegible]	1	1	1	1	1	1	1	1	1	1	25
26	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	120	1	1	1	1	1	1	1	1	1	1	26
27	0	0	0	0	0	0	0	0	0	1	1	1	1	1	121	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	27
28	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	119	1	1	1	1	1	28
29	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	-16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	29
30	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-15	1	1	1	0	30
31	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	0	0	31
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	

Figure 1: Grid block configuration

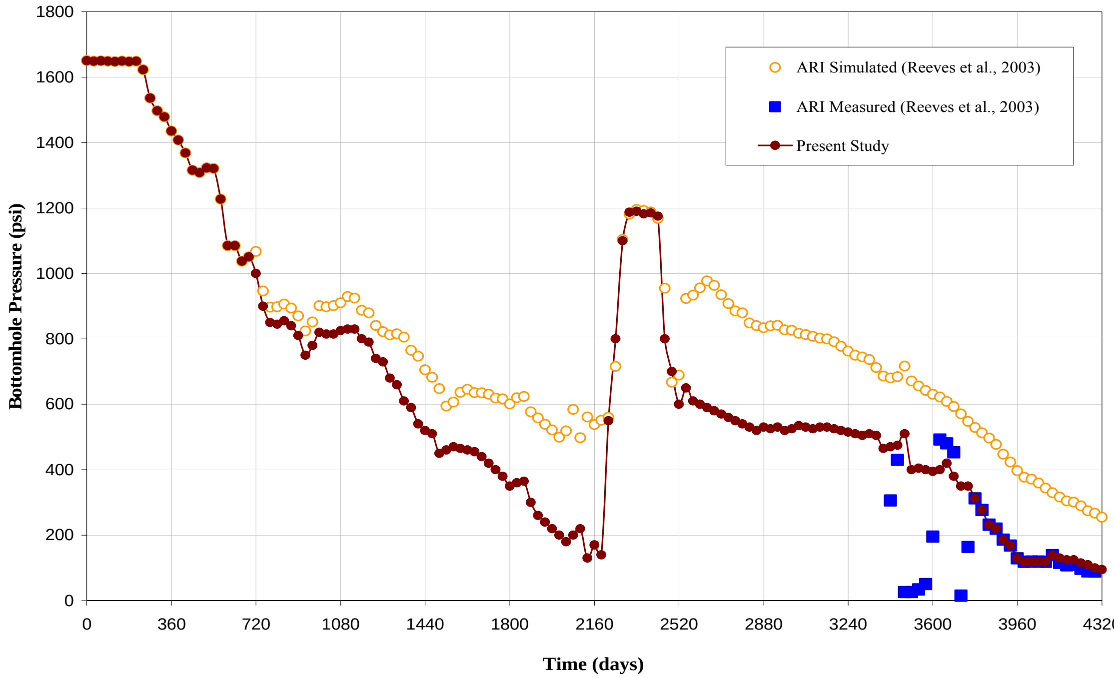

Figure 2: Comparison of bottomhole pressure at producer well # 113.

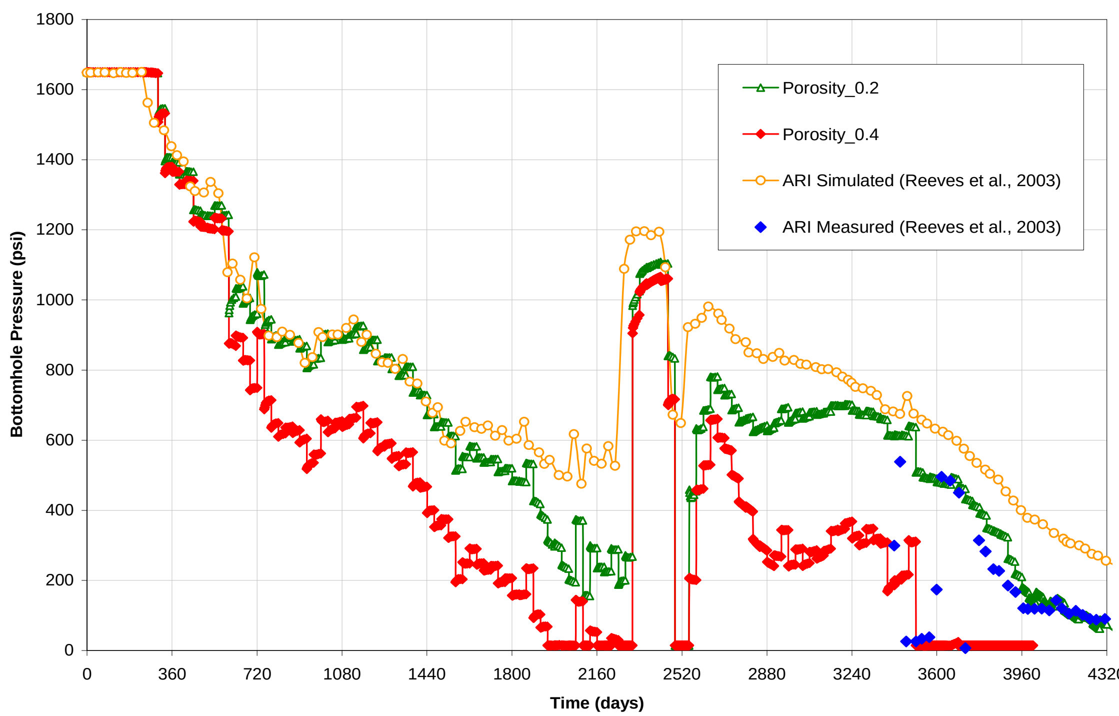

Figure 3: Influence of cleat porosity on the bottomhole pressure at producer well #113.

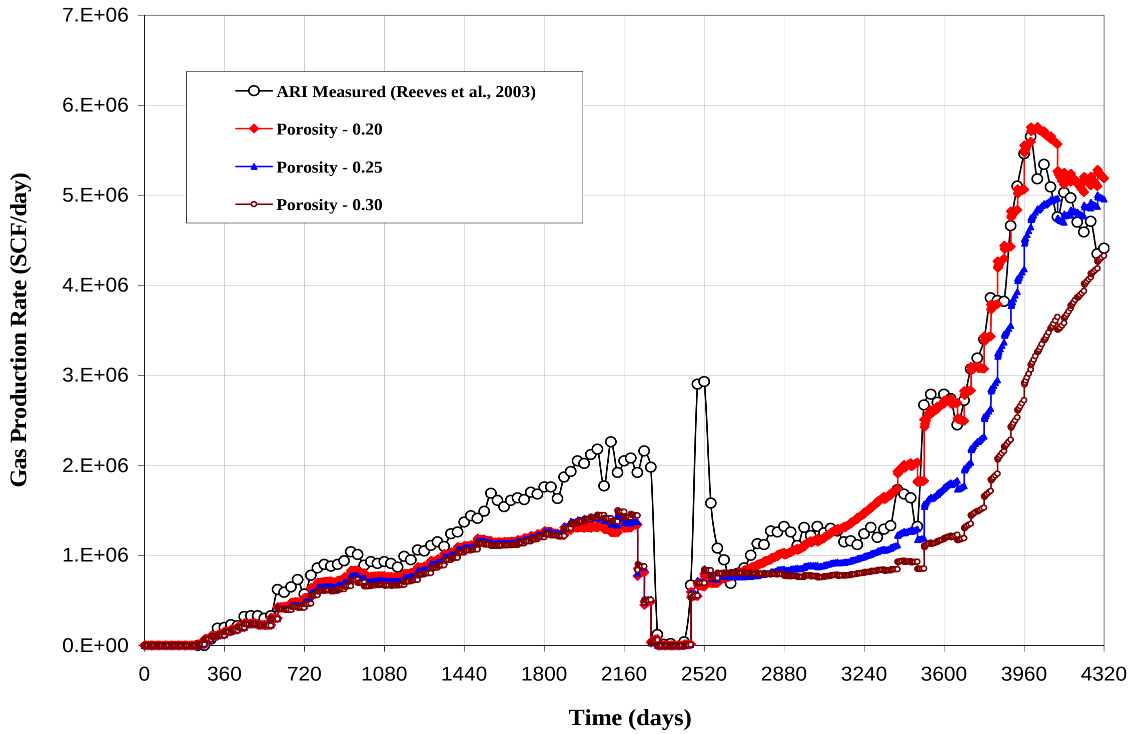

Figure 4: Influence of cleat porosity on gas production rate at producer well # 113.

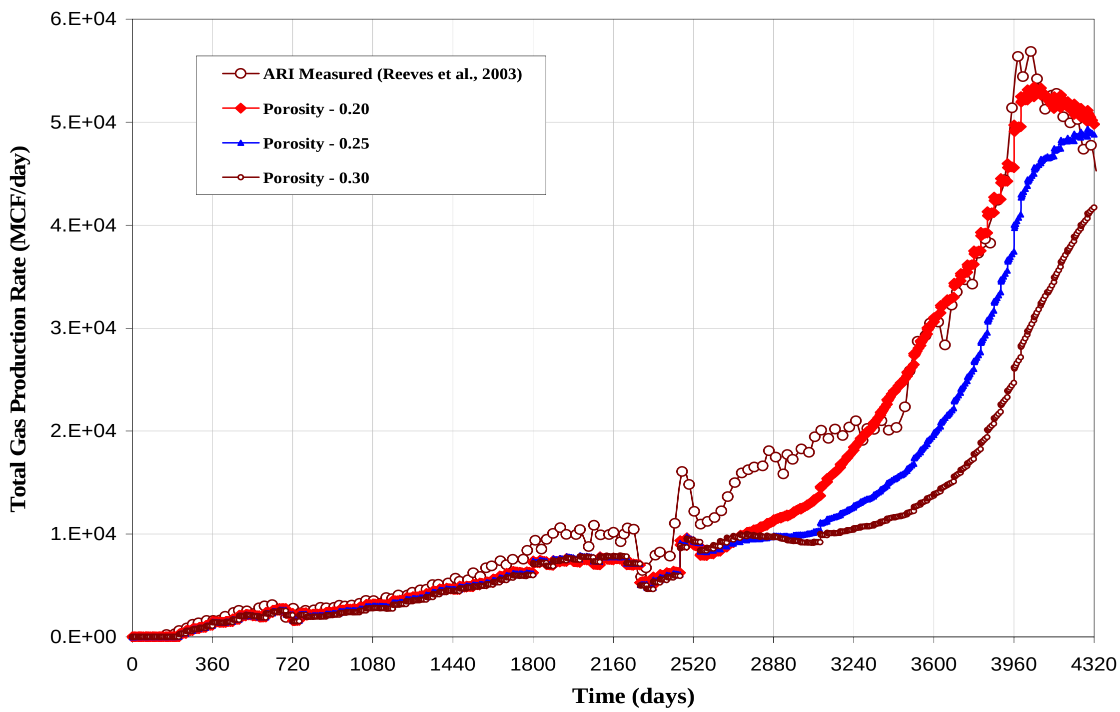

Figure 5: Influence of cleat porosity on total gas production rate.

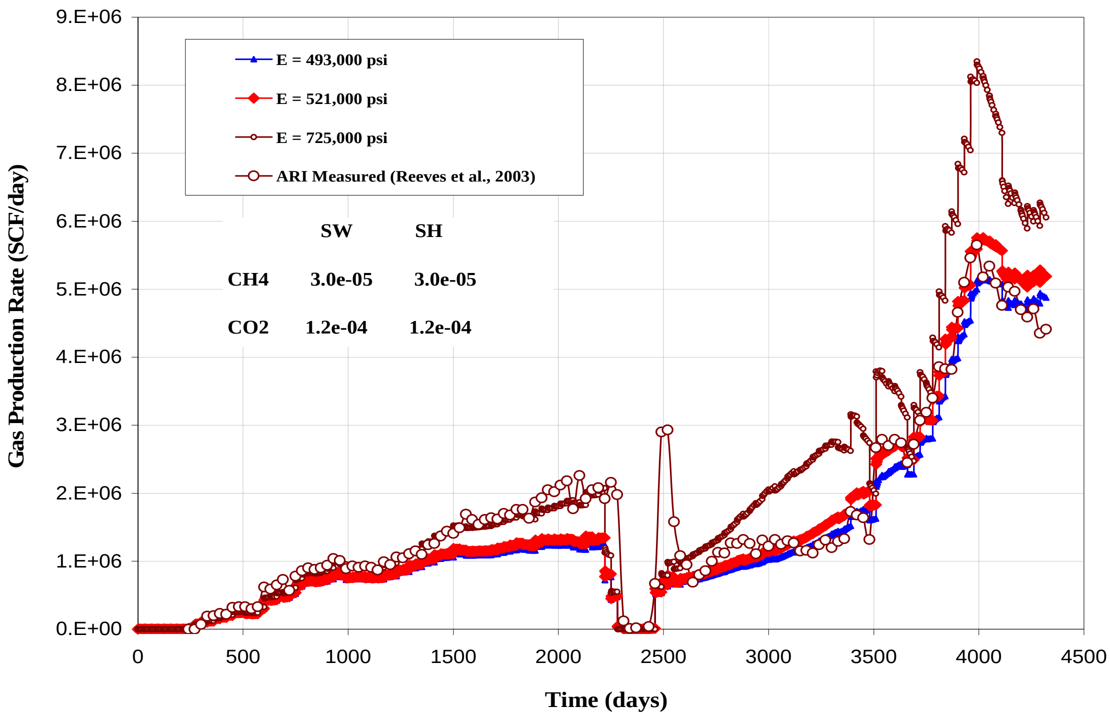

Figure 6: Influence of elastic modulus on gas production rate at producer well # 113.

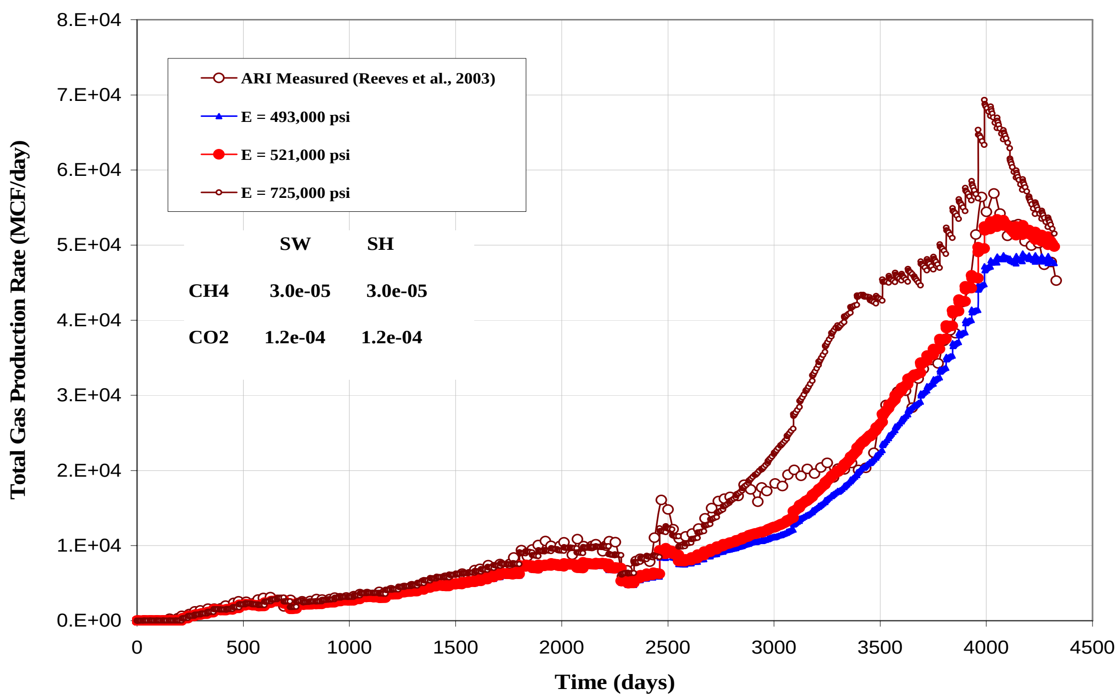

Figure 7: Influence of elastic modulus on total gas production rate.

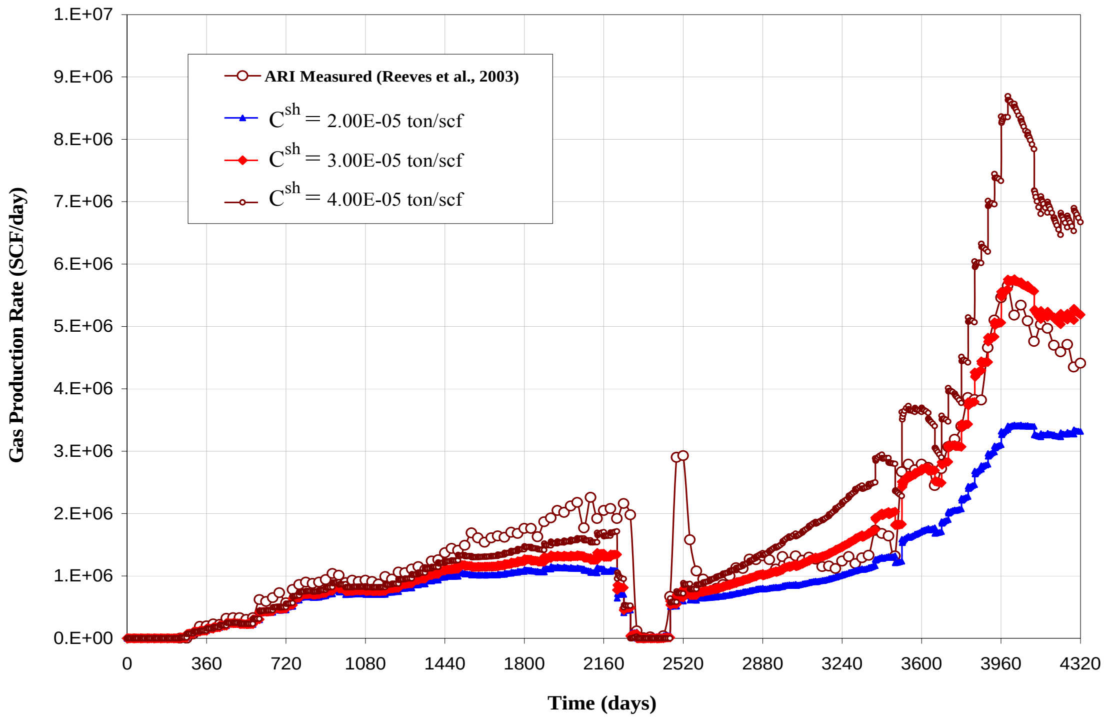

Figure 8: Influence of shrinkage on gas production rate at producer well # 113.

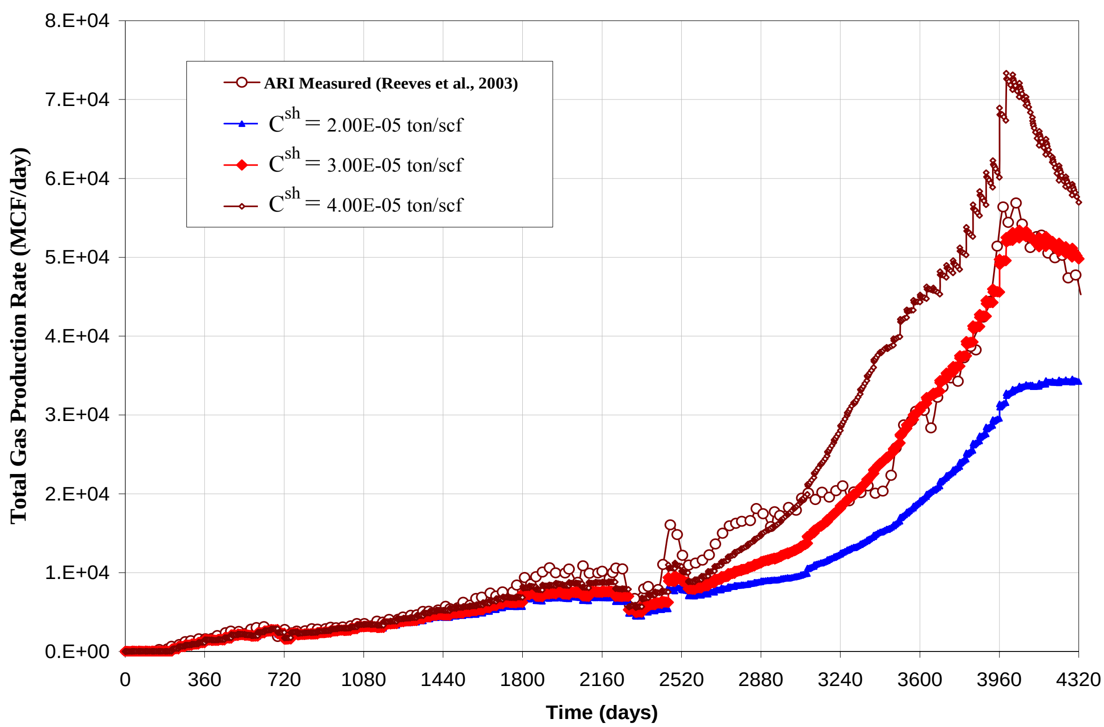

Figure 9: Influence of shrinkage on total gas production rate.